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THE DEVELOPMENT OF NEW HIGH-STRENGTH TITANIUM ALLOYS

- USSR -

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# FOREWORD

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SOME PROBLEMS IN THE THEORY OF HEAT RESISTANCE  
AND THE DEVELOPMENT OF NEW HIGH STRENGTH TITANIUM ALLOYS

- USSR -

Following is a translation of an article by I. I. Kornilov in the Russian-language periodical Izvestiya Akademii Nauk SSSR, OTN, Metallurgiya i Toplivo (Notices of the Academy of Sciences USSR, Division of Technical Sciences, Metallurgy and Fuel), Moscow, No. 4, 1959, pages 190-199. It is a curtailed report on the general meeting of the Division of Technical Sciences of the Academy of Sciences USSR held 23 December 1958.

1. Physical Chemical Fundamentals of Heat Resistance. The theory of heat resistance is a part of the general problem of the strength of metals and alloys. It has developed from modern views on the physics and chemistry of the solid state, of metallurgy, and also of the theory of the strength of plastics.

In the physical theory of heat resistance the subjects of study are the problems of the mechanism of plastic deformation during creeping, the processes of the breakdown of metals and alloys under the prolonged action of stresses, and the factors affecting heat resistance.

The works of many Soviet and foreign scholars have been devoted to a study of these problems, and they have been published in articles, review articles, and monographs<sup>1-10</sup>.

In Reference 1 four mechanisms of plasticity are established, including: 1) displacement or dislocation; 2) amorphous diffusion; 3) interphase transfer by means of solution and deposition; 4) internuclear transfer when recrystallization is present.

In the investigations of Reference 5 great weight is given to the diffusion mechanism of plasticity, which plays an important role in the development of creeping and in the breakdown of metals at high temperatures.

The part played by diffusion in the heat resistance of alloys has also been considered in the works of other authors<sup>11-13</sup>.

From the point of view of modern physical notions on the strength of materials, the dislocation theory<sup>6,7</sup> has proved to be of great importance in recent studies of the mechanism of creeping.

Starting from the imperfection of crystals and from the presence in them of vacant sites and defects, it can be assumed that local strains and shears resulting from small stresses are possible, which is not the case in perfect crystals.

The fundamental physical factors in heat resistance according to Reference 5 are: 1) the strength of the interatomic bond, and 2) the structure of metals and alloys.

The strength of the interatomic bond is the basic factor that determines the temperature at which the metal can resist deformation. It is determined by the various parameters of the solid substance: the heat of sublimation, the energy of activation of diffusion, the size of the mean square deviation of the atoms during thermal vibrations, etc. The temperature of the change from resistance to deformation to the diffusion transfer of the atoms depends not only on the strength of the interatomic bond but also on the size of the stresses, which lead to an increase in diffusion and determine the direction of diffusion.

In the theory of heat resistance, great importance is given to the structure of metals and alloys. In References 2 and 3 the role of heterogeneous structure in the heat resistance of metals and alloys was considered. The development of barriers, which are included in the form of metallic phases, should display a marked resistance to plastic strain or creeping in a homogeneous medium. The mechanism of fatigue and breakdown of metals at high temperatures is explained by the data of Reference 3 and by other authors by the appearance of local cracks, principally at the boundaries of the crystals nuclei, and by their subsequent growth under the action of stress. The appearance of these cracks can be explained by the structural inhomogeneity and by the concentrations of stresses along the boundaries of these inhomogeneities. Of particular importance in the heterogeneity of the structure of alloys and in heat resistance are submicroscopic inhomogeneity and the separation of phases in the finely dispersed state. In this state they display a great resistance to plastic strain, and at a definite stage of their coagulation they lead to an increase in creeping<sup>14-16</sup>.

In the present article there will be considered some physical chemical problems in investigations of heat resistance and a determination of the variation of heat resistance as a function of the type of chemical interaction of the metals.

Before considering the problems of determining these relationships, the methods by which these problems are studied should be mentioned.

2. Methods of Investigating the Heat Resistance of Metallic Alloys. Many of the methods of investigating heat resistance are described in a book<sup>17</sup>.

Among these the simplest and most practical are the methods of light temperature hardness, prolonged hardness, creeping studies by the deflection of standard rings of the same cross-section, and the centrifugal method of deflection.

These methods, although they are not standard, make it possible to obtain the characteristics of the heat resistance of metallic alloys that are comparable with standard methods. They are important in order to establish the general relationships relating changes of the properties of

heat resistance as a function of chemical composition, of the structure of alloys, of various physical chemical transformations in the solid state, and of the temperature and other factors of heat resistance.

The centrifugal method of strain by bending samples at high temperatures<sup>18, 19</sup> is one of the simplest and most practical methods, and it makes it possible to experiment simultaneously with one piece of equipment on a large number (up to 24) of samples of moderate size and weight.

Fig. 1 shows one of the most recent models of a centrifugal machine<sup>19</sup> for investigating strength through bending, which was developed by the author and V. F. Prokhanov. It is mounted on an ordinary laboratory bench and permits the simultaneous investigation of 24 samples. With the machine it is possible to carry out investigations on samples with small amounts of strain (such as are applicable under the conditions of creeping in alloys), and also the investigation of the prolonged resistance of samples up to the breakdown point.

By determining periodically the size of the bending (in millimeters, degrees, or the percentage increase in the length of an external thread) it is possible to obtain experimental data for curves of the amount of the strain (bending) versus the time of the strain. As observations on a large number of samples have shown, curves of the rate of straining as a function of strength have various but quite definite forms (Fig. 2).

Under the same initial conditions samples of different strengths are deformed at different rates.

As an example, Fig. 3 shows a series of curves of changes in a measure of the bending of in millimeters for alloys of different compositions for the binary system Ni-Cr resulting from experiments at 800° with an initial stress of 12.3 kg/mm<sup>2</sup>. The strain curves for various compositions of alloys characterize their strength.

After the study and analysis of the various measurements for determining heat resistance by the centrifugal method, we have adopted the time required to attain a given degree of strain.

This procedure is the most accurate and objective for characterizing the heat resistance of alloys of different strengths.

3. Physical Chemical Bases of Heat Resistance. The strength of the interatomic bond of pure metals is an intrinsic quantity. It is characterized by the parameters introduced above and is an individual property of a given simple substance.

The strength of the interatomic bond (between like atoms of a pure metal) can change significantly as a result of chemical interaction of metals with other elements. Outstanding here are bonds between different kinds of atoms, or chemical bonds, which have a different strength from the simple interatomic bonds in pure metals.

The study of the role of chemical interaction of metals with each other or with metalloids in variations of the heat resistance of metallic alloys is a fundamental subject of the physical chemistry of heat resistance. It is of the greatest importance here to establish the

dependence of the heat resistance of metallic alloys on the fundamental properties of their constituents and the nature of the interaction of these. This represents a further development of the well known work of N. S. Kurnakov concerning the physical chemical analysis of metallic systems<sup>20,21</sup> and of other authors on the study of the temperature dependence of the strength of metallic systems<sup>22,23</sup>.

Based on theoretical views of the physical chemistry of heat resistance, we shall start from the fact that strengthening of metals occurs on account of the following fundamental types of chemical interaction of metals: 1) the formation of metallic solid solutions; 2) chemical reactions in the crystal or phase transitions in the solid state; 3) the formation of metallic compounds; 4) a different relation of the stable phases in heterogeneous systems.

Investigations of the variation of the heat resistance of metallic systems as a function of the types of chemical interaction listed above have been made by the centrifugal method described above.

Studies have been made of the heat resistance of continuous and bounded solid solutions<sup>24</sup>, of systems with transition reactions in the solid state (crystal chemical reactions), of the formation of metallic compounds<sup>25-28</sup>, of heterogeneous systems having no regions with solid solutions, and of interacting solid-state phases. As a result of these investigations, the basic relationships of the change of this property as a function of the chemical compositions and structure of metallic systems have been established.

The applications of various methods of investigating heat resistance has carried the investigations of other authors <sup>22,23,29-32</sup> along the same lines.

A brief consideration of the problems of the high-temperature strengthening of metals resulting from the above-mentioned basic types of interaction is given below.

1. Strengthening because of the formation of continuous solid solutions. According to current views it can be taken as established that the fact of the formation of solid solutions of metals causes an increase in the strength of the chemical bond.

In this respect the strength of the bond between different kinds of atoms is larger than that of the simple interatomic bond between like atoms of pure metals. This is connected with the presence of an interaction between the external electrons of the atoms of the metal solvent and of the element dissolved. It shows up as an increase in the specific electrical resistance, distortions of the crystal lattice of solid solutions, and changes in other properties.

The degree of change of these properties depends on their individual nature and on the concentration of elements dissolved in the metal.

Elements of the periodic system having a different electronic structure display a different degree of mutual solubility and have individual characteristics influencing the properties of solid solutions of metals,

including the strength of the chemical bond. Therefore it can be considered that analog metals having the same external electron structure have a less significant effect on the properties of solid solutions than elements with a greatly different number of external electrons.

The strengthened state of solid solutions is in general maintained on heating at much higher temperatures than for pure metals. This is connected with the fact that chemically different atoms are more strongly bound with atoms at the corners of the solvent-metal lattice and remain in a stable state at much higher temperatures than atoms in the lattice of the pure metal. This is confirmed by experimental data on the change of hardness and heat resistance as a function of temperature for several continuous solid solutions of metals. In one of the papers of V. P. Shishokin<sup>22</sup> there are data on the change of hardness of continuous solid solutions of the system silver-gold as a function of temperature (Fig. 4). Despite the fact that these metals are analogs, up to the temperature studied by the author (300° C) the strengthening of the solid solutions is maintained, and the flat type of maximum in the composition-hardness curves corresponds approximately to a 50% ratio of the constituents.

In a paper published by the author in 1949<sup>24</sup>, studies were made of the heat resistance of continuous solid solutions of the system copper-nickel.

In Fig. 5 are shown, together with the solidus and liquidus curves for this system, changes in the deflection reading after one hour or the bending strain of samples at 900°. The pure metals - copper and nickel - and dilute solid solutions were quickly deformed here and reached a maximum value of deflection readings.

Solid solutions from the region of the maximum concentration of the components were almost undeformed after one hour. Plotting the deflection reading after one hour in Fig. 5, one finds a flat minimum in the center part of the system, which corresponds in any given case to the flat maximum in the heat resistance of solid solutions in this region. These conclusions have been confirmed by recent work studying heat resistance by the centrifugal method and the high-temperature hardness of these same systems in the temperature range from 600 to 900°.

Thus, investigations of the heat resistance of continuous solid solutions of metals show that the resistant state is maintained up to high temperatures. On the basis of these data it can be considered that there is no confirmation for the hypothesis expressed in the literature<sup>23</sup> that it is possible at temperatures above 600° for the curve to change from convex to concave.

The smooth type of increase of heat resistance in continuous solid solutions is maintained only in systems in which there is no transition to the solid state. The two systems considered above are of this type. A significant change in heat resistance may occur in those continuous solid solutions where crystalline reactions with compound formation takes place.

Changes in heat resistance in the system Fe-Ni may be given as an example.

At temperatures below  $500^{\circ}$  in this system, there is formed from the austenite solid solution of the  $\gamma$ -phase the compound  $\text{Ni}_3\text{Fe}$ , the distribution region of which is given in the upper part of Fig 6. In the lower part of Fig 6 there are given curves of composition-heat resistance at  $600$  and  $450^{\circ}$  33. They show the presence of a flat maximum of the heat resistance in the region of the composition of the compound  $\text{Ni}_3\text{Fe}$  at a temperature of  $600^{\circ}$ . This is somewhat higher than its dissociation temperature. It is apparent that along this isotherm there is still close-range order in the region of the dissociated state of the compound. At  $450^{\circ}$ , which is below its temperature of formation, i.e. in the region of stability of the compound  $\text{Ni}_3\text{Fe}$ , the composition-heat resistance curve is of a singular type with a sharp maximum corresponding to the composition of the compound  $\text{Ni}_3\text{Fe}$ . The same type of composition-heat resistance diagram in the region of this compound has been described in a paper\*, and is also shown by examples of other compounds, in particular the compound  $\text{MgCd}^{25}$ . (\*K. A. Opisov. Thesis for the degree of Doctor of Technical Sciences, Institut Mashinovedeniya [Mechanical Engineering Institute] Academy of Sciences, USSR, 1949.)

Thus, crystalline reactions in continuous solid solutions connected with the formation of compounds are displayed as a sharp change in the heat resistance as a function of the composition of like systems.

## 2. Heat resistance in systems with limited solid solutions.

A large influence on the increase of heat resistance in metals is displayed by elements of limited solubility. Strengthening of this kind is also connected with the chemical nature of solid solutions. The interaction between the electrons of atoms of the solvent and the solute causes an increase in the strength of the chemical bond of atoms in the lattice of the solid solutions.

Elements of limited solubility display in this case an individual effect on heat resistance which is determined by the electron structure of these elements. These views are confirmed in observations of the effect of a number of elements of limited solubility on the increase in heat resistance. This is shown, for instance, in nickel according to the data of a number of investigators.

Fig. 7 shows the author's data on the effect of Zr, Nb, and Mo, which are elements in the sixth series and fifth period of Mendeleev's periodic table, on the heat resistance of nickel.

The solubility of these elements increases from a negligible value for zirconium up to a significant concentration for niobium and molybdenum. The curves of Fig. 7 show the change in the time required to reach a particular deflection reading (5 mm) as a function of the amount of the elements present for  $800^{\circ}$  and a stress of  $4 \text{ kg/mm}^2$ .

In the Ni-Zr system, where there is an extremely limited solubility (0.5% Zr) the heat resistance of the nickel is quite insignificant and increases almost additively as the zirconium content increases.



In the systems Ni-Nb and Ni-Mo within the limits of solid solutions of nickel the heat resistance is increased significantly with an increasing concentration of the dissolved elements.

Here the magnitudes of the heat resistance are significantly larger than in the system Ni-Zr, which has a negligible region of solid solutions.

One can give curves of the change in the rate of creeping (by a standard method) of nickel as a function of the concentration of elements dissolved in it. Reference 34 gives data for Co, Fe, Ti, and W. As can be seen from the curves (Fig. 8), cobalt and iron, which are close analogs of nickel, form with it continuous solid solutions and cause an insignificant effect in decreasing the rate of creeping of nickel.

Titanium and tungsten, on the other hand, are different from nickel in their electron structure and have a limited solubility over a considerable range. They sharply lower the rate of creeping of solid solutions with nickel (Fig. 8), i.e. they increase the heat resistance.

From this it follows that if elements form limited solid solutions with a significant concentration, they strengthen the metal solvent, and the strengthening increases with an increase of concentration of the elements in the solid solution and is maintained up to high temperatures.

Many limited solid solutions of metallic systems are characterized by the fact that when they reach a limiting solubility crystalline reactions occur in them. These reactions are connected with the formation of additional phases from the supersaturated solid solutions. Depending on the conditions of temperature, the degree of supersaturation, and the nature of the phases formed, these phases separate out in the form of finely dispersed or coagulated structural constituents. The type and the means of formation of these phases and their structural properties are reflected in the change of heat resistance of the alloys in this transition region of the composition diagram of systems with limited solid solutions<sup>14-16</sup>.

The transition region from homogeneous solid solutions to heterogeneous structures is characterized by an increase in heat resistance on the diagram of composition versus heat resistance for such systems<sup>25-28</sup>.

The classical system of mutually limited solubility, with variable solubility of components and with no compound formation in the region of the two solid solutions is given by the system Ni-Cr. The heat resistance of this system was studied by the author at temperatures of 800° and 1000°, and the results are given in Fig. 9<sup>28</sup>. As can be seen from the curves of Fig. 9, the transition regions from mutually limited solubility of the components to the region of heterogeneous structures are characterized by a flat maximum in the heat resistance. These maxima appear for both isotherms. Depending on the degree of weakening of the  $\delta$  and  $\alpha$  limited solid solutions with temperature, the values of the maxima on these two isotherms switch positions. In the two-phase region of the system that first has separation of structural constituents, the lower values of the heat resistance vary linearly.

The manifestation of chemical affinity is extremely characteristic in a system with limited solid solutions and with the formation of a metallic compound in the solid state. In Fig. 10 there is given as an example the change of heat resistance in the system Ni-Mo, which has the formation of limited solid solutions and the compounds  $\text{Ni}_4\text{Mo}$  and  $\text{Ni}_3\text{Mo}$ . As has been shown by the author's investigations, over the range of the limited solid solutions the heat resistance increases at  $800^\circ$  and reaches a maximum value in the transition region (Fig. 10). The formation of the compound  $\text{Ni}_4\text{Mo}$  by a peritectoid reaction is shown by a second maximum of the heat resistance at the composition of this compound.

Variations of the heat resistance of metallic systems with limited solid solutions have been studied by the author for many cases. The author has been concerned with systems containing Ni, Fe, Al, Ti, Nb and other metals.

In all cases it has been found that the heat resistance of the chief metal increases on account of the formation of solid solutions, and the maximum heat resistance is reached in the regions described above connected with the occurrence of crystalline reactions in limited solid solutions.

Thus it can be assumed that in the change of the heat resistance of metals an important part is played by limited solid solutions undergoing transformations in the solid state. The greatest strengthening is reached in the transition regions of the composition diagram of metallic system from solid solutions of limiting saturation to the system on account of the breakdown of the supersaturated solid solutions and the separation out of a finely dispersed extra phase. Here lies the importance of crystalline reactions in the problem of heat resistance.

The region of maximum strengthening in such systems is not constant. It depends on a temperature factor. At higher temperatures the maximum values of the heat resistance go over from the region of heterogeneous to the region of homogeneous solid solution, crossing the boundary of the limiting solubility in the system over a definite temperature range.

In our investigations of three sample systems there was established this kind of a displacement of the maxima of heat resistance as a function of the temperature factor<sup>35-37</sup>. These investigations, which make it possible to explain different types of composition-heat resistance diagrams, require independent consideration.

3. Strengthening of metals due to the formation of metallic compounds. It is well known that metals interacting with each other or with a number of metalloids form, in addition to solid solutions, compounds with a metallic type of bond. Such compounds, the so-called metallic ones, are formed: 1) because of crystalline reactions, 2) on crystallization of liquid solutions.

Both these and other compounds are characterized by the crystal structure occurring in them, by the regular arrangement of atoms in the lattice and by individual properties. The strength of the chemical bond between the atoms in such compounds is higher than those occurring in their components. The atoms in them show more resistance to strain at

high temperatures than in the pure metals and in solid solutions.

It might be expected that the large strength of the chemical bond in metallic compounds would be reflected in the heat resistance of such compounds.

It has been shown above that compounds which are formed because of crystalline reactions (from solid solutions or peritectoid reactions of  $\text{Ni}_3\text{Fe}$ ,  $\text{Ni}_4\text{Mo}$ , etc.) have a higher value of the heat resistance than do the phases associated with them (Fig. 6 and 10). The compositions of these compounds on composition-heat resistance diagrams are characterized by the points of the maxima.

A high heat resistance is also to be found in compounds that are formed on crystallization.

The author has studied this problem for metallic compounds of nickel with titanium, niobium, and tantalum, corresponding to the compositions  $\text{Ni}_3\text{Ti}$ ,  $\text{Ni}_3\text{Nb}$  and  $\text{Ni}_3\text{Ta}$ <sup>38</sup>. The relative heat resistance of these compounds has been studied by the centrifugal method (deflection) at  $1030^\circ$  and with a stress of  $6 \text{ kg/mm}^2$ . For purposes of comparison, in addition to samples of these compounds, alloys were measured for their heat resistance under the same conditions. These were alloys of Ni-Nb (10% Nb) and Ni-Ta (7.5% Ta), the compositions of which correspond on the composition-heat resistance diagram to the maximum values of heat resistance at  $800^\circ$ . Fig. 11 shows a series of curves of the change of the deflection reading of samples of the alloys and the compounds as a function of the time of observation at  $1030^\circ$  and  $\sigma = 6 \text{ kg/mm}^2$ . As can be seen from the curves, the alloys of nickel with niobium and tantalum are bent very quickly and under these experimental conditions are not at all heat resistant. The compounds that were studied have a much lower rate of creeping (for bending deformation) than the nickel alloys. They were deformed by a negligible amount after 100 hours.

On comparison of the curves of bending deformation of these three compounds of nickel with different elements, the individual nature of the heat resistance of these compounds is made apparent. The compound  $\text{Ni}_3\text{Ti}$  is less heat resistant, and the compound  $\text{Ni}_3\text{Nb}$  is more heat resistant; the compound  $\text{Ni}_3\text{Ta}$  occupies an intermediate position between the first and second compounds.

Thus, metallic compounds have higher values of heat resistance than the pure metals and solid solutions based mainly on these metals, and each compound possesses individual heat-resistance properties.

These conclusions are also in agreement with the high heat resistance of such refractory compounds as the carbides, silicides, and borides of metals. These compounds are very hard but brittle, and as a result they have a limited value as heat resistant materials in their pure forms. Therefore they find technical application as additives in compositions of these compounds with plastic constituents (metals or alloys), which, lowering their brittleness at the same time as their heat resistance, make them suitable for use in manufactured objects<sup>39</sup>.

The high heat resistance of metallic compounds is valuable for strengthening solid solutions in simple and multicomponent systems with limited solid solutions, when these compounds are formed from super-saturated solid solutions in a finely dispersed state and maintain this state over a long time of observation. However, these same highly resistant metallic compounds are valuable in strengthening alloys in heterogeneous systems, in which there are no significant regions of solid solutions.

4. The heat resistance of heterogeneous systems without significant areas of solid solutions. In metallic systems where there is no mutual solubility of the components or where extremely limited formation of solid solutions takes place, the conditions are absent for heat resistance of the basic metal on account of solid solutions or the dispersed separation of additional phases. In such systems it can be assumed that the strengthening of alloys will proceed on account of changes of structure and quantitative changes of the proportion of the phases. Here, as the amount of a second phase of greater heat resistance than the first is increased, the heat resistance of the alloys will increase, and as a phase of less heat resistance increases it will decrease. This kind of relation between the amount of the phases in the structure of alloys and the heat resistance can be assumed in case there is no interaction between the phases in such systems. On maintaining these conditions the heat resistance, as well as other properties, will change additively or nearly additively.

Recent experimental investigations have established this type of change of heat resistance in a number of heterogeneous systems without significant regions of solid solutions.

The heat resistance in such systems has been studied for Cu-Zr and Cu-Cr by the method of high-temperature hardness in several articles<sup>30,31</sup>, and by the author for Ni-Zr by the centrifugal method. In Figs. 12 and 13 the composition-heat resistance diagrams are compared with the phase diagrams for the systems Cu-Zr and Ni-Zr respectively.

Zirconium, as can be seen from Figs. 12 and 13, having an unfavorable ratio of atomic volume with copper and nickel, has extremely limited formation of solid solutions with them.

Curves of change of high-temperature hardness at a corresponding temperature (0.6  $T_{melt.}$ ), according to the data of Reference 31, in the system Cu-Zr and of the change of heat resistance (from bending) at 800° in the system Ni-Zr are of the same type.

In these systems, with an extremely small region of formation of solid solution, the strengthening of Cu and Ni proceeds along a smooth curve. It increases as the amount of an additional phase in the form of refractory and heat-resistant compounds, such as  $Cu_4Zr$  in the system Cu-Zr and  $Ni_4Zr$  in the system Ni-Zr, increases.

The same type of smooth change of high-temperature hardness as a function of the composition occurs in the system Cr-Zr (on the part of chromium); the system has an extremely limited solubility of

chromium in copper<sup>31</sup>. A smooth decrease in the long-term resistance at 850, 900, 950, and 1000° (Fig. 14) is observed in the heterogeneous system TiC with the triple alloy Ni-Cr-Co as the content of the triple alloy increases<sup>40</sup>. This system is also characterized by a very insignificant mutual solubility of the phases.

Thus, in metallic systems with extremely limited regions of solid solutions and without interaction between the phases in the solid state, the heat resistance changes smoothly as a function of the type and the quantitative proportion of these phases.

In concluding a consideration of the materials mentioned above it can be taken as established that the heat resistance of metallic systems is definitely dependent on the type of chemical interaction and is connected with the phase diagram of these systems.

The experimentally observed dependences of the heat resistance on the composition and structure of alloys is expressed by specific diagrams of composition versus heat resistance. Various types of composition-heat resistance diagrams correspond to various types of chemical interaction between metals. This problem will be dealt with in general in a forthcoming article.

#### Conclusions.

1. Variations of the heat resistance of metals as a function of the type of chemical interaction between the components in binary systems is established in this paper.

2. The heat resistance of metallic systems is defined by four basic types of interaction: 1) the formation of solid solutions; 2) crystalline reactions; 3) the formation of metallic compounds; 4) different ratios of the stable phases in heterogeneous systems.

3. The strengthening of metals in continuous solid solutions is mentioned at significantly higher temperatures than has hitherto been supposed.

4. With limited formation of solid solutions high-temperature strengthening increases as the concentration of dissolved element increases and the maximum heat resistance is reached at the transition region between solid solutions of definite saturation to heterogeneous structures with a finely dispersed separation of the additional phase.

5. Metallic compounds, which are formed from solid or liquid solutions, are characterized by a higher heat resistance than do their constituent components or solid solutions made up of these compounds.

6. In heterogeneous systems with an extremely limited definite solubility of the components and an absence of interaction between the phases in the solid state, the heat resistance of alloys depends on the ratios and the heat resistances of the phases participating in the system. It changes linearly as a function of the quantitative proportion of the phases in such systems.

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Figure Appendix

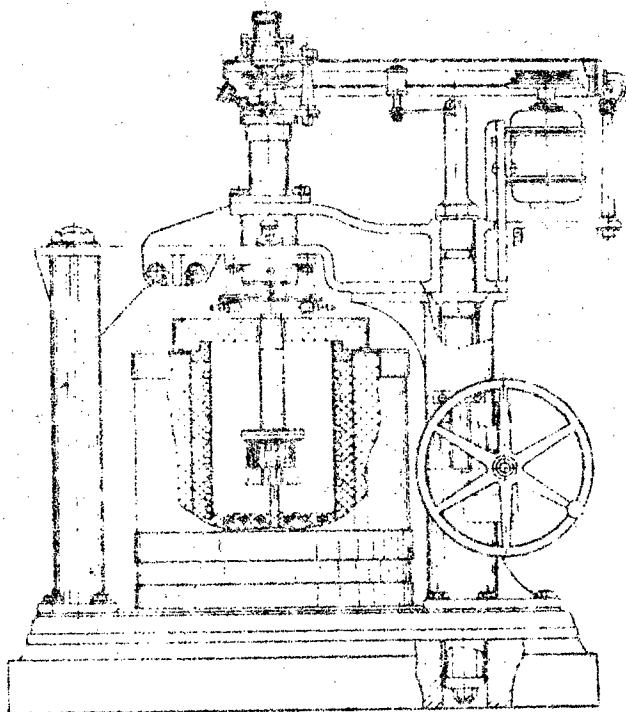


Figure 1. Centrifugal machine for the investigation of heat resistance.

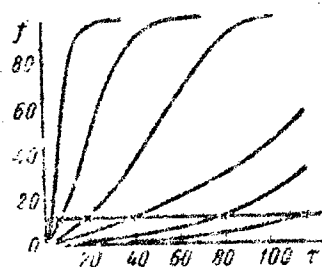


Figure 2. Typical curves of deformation during the investigation of creeping by the bending method.  $f$  is the deflection reading in mm,  $\tau$  is the time in hours.

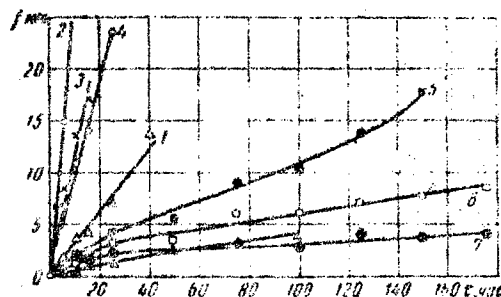


Figure 3. A series of actual curves of the bending of alloys of the system Ni-Cr at 800° and  $\sigma = 12.3$  kg/mm<sup>2</sup>. Cr content: 1 - 30 %, 2 - 55 %, 3 - 70 %, 4 - 80 %, 5 - 88 %, 6 - 90 %, 7 - 93 %, 8 - 95 %.

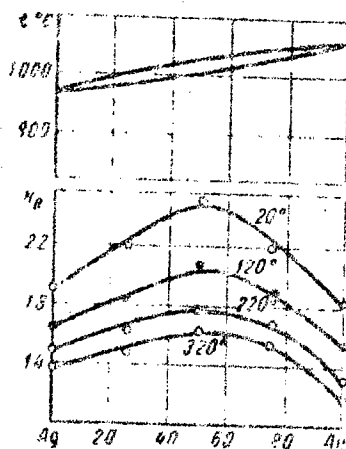
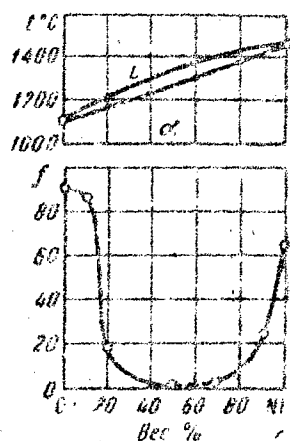
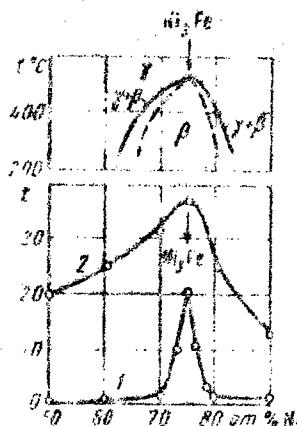


Figure 4. Diagram of composition versus hardness up to 300° for alloys of the system Ag-Au.



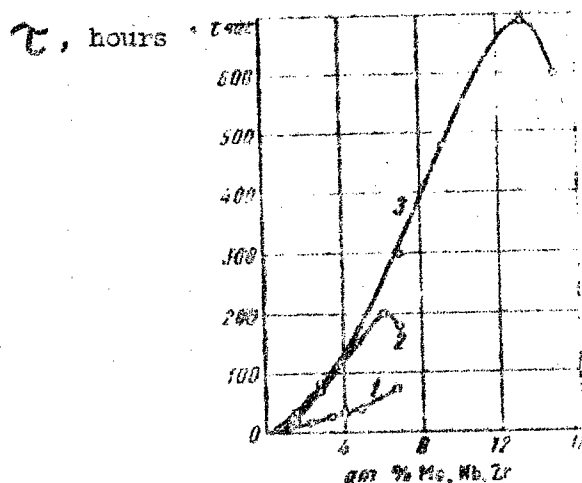
Cu 20 40 60 80 Ni  
Weight %

Figure 5. Diagram of composition versus heat resistance at 900° for alloys of the system Cu-Ni, with a time of deformation of 1 hour.  $f$  is the deflection reading in mm.



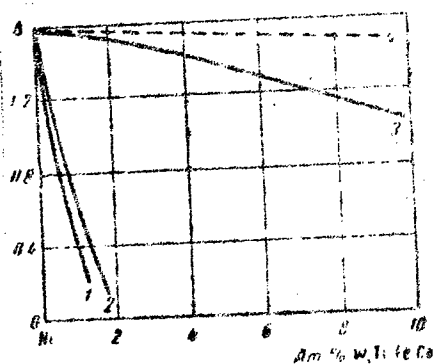
at. % Ni

Figure 6. The region of distribution of the compound  $\text{Ni}_3\text{Fe}$  in the system Fe-Ni and the diagram of composition versus heat resistance; 1 - 4500 and  $\sigma = 30 \text{ kg/mm}^2$ , 2 - 6000 and  $\sigma = 10 \text{ Mg/mm}^2$ ,  $\tau$  is the time for the indicator to reach 10 mm.



at. % Mo, Nb, Zr

Figure 7. The effect of Zr, Nb, and Mo on the heat resistance of nickel at 800°  $\sigma = 4 \text{ kg/mm}^2$ ; 1 - the system Ni-Zr, 2 - the system Ni-Nb, 3 - the system Ni-Mo.



at. % W, Ti, Fe, Co

Figure 8. The effect of Co, Fe, Ti, and W on the rate of creeping  $\Delta$  (m/m, 1000 hrs) of nickel at  $700^\circ\text{C}$ ,  $\sigma = 3.9 \text{ kg/mm}^2$ ; 1 - the system W-Ni, 2 - the system Ti-Ni, 3 - the system Fe-Ni, 4 - the system Co-Ni.

$t^\circ\text{C}$   
 $\tau$ , hours

$\tau$ , hours

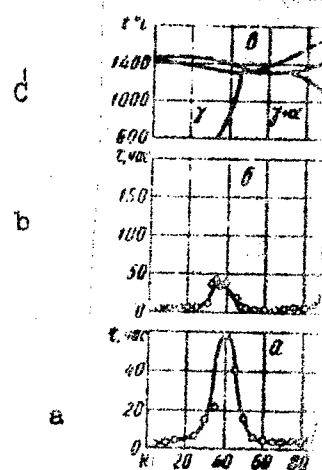


Figure 9. Diagrams of composition versus heat resistance for the system Ni-Cr; a -  $1000^\circ\text{C}$  and  $\sigma = 2.7 \text{ kg/mm}^2$ ; b -  $800^\circ\text{C}$  and  $\sigma = 12.3 \text{ kg/mm}^2$ ; Indicator reading 5 mm.

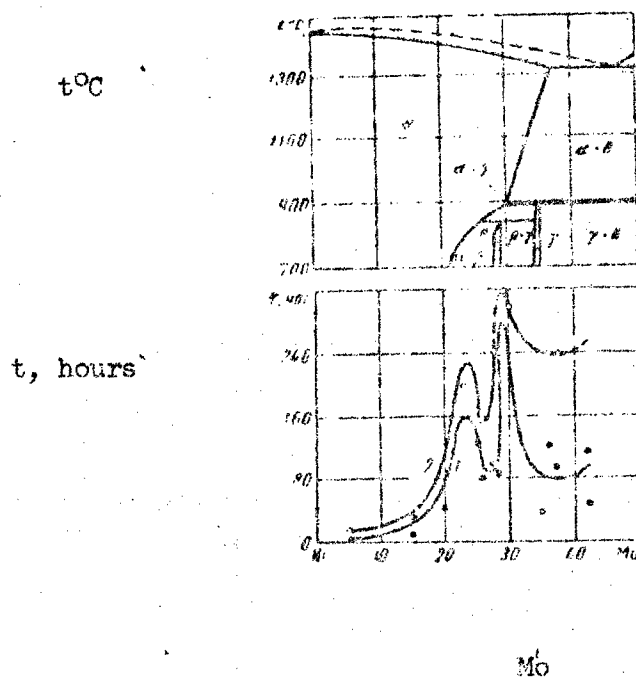


Figure 10. Diagram of composition versus heat resistance for the system Ni-Mo at  $800^{\circ}$  and  $\sigma = 17 \text{ kg/mm}^2$  [sic]; 1 - time of reaching an indicator reading of 5 mm, 2 - time to breakdown (the dotted line indicates that the sample had not broken down at  $\sigma = 17 \text{ kg/mm}^2$  after the time shown).

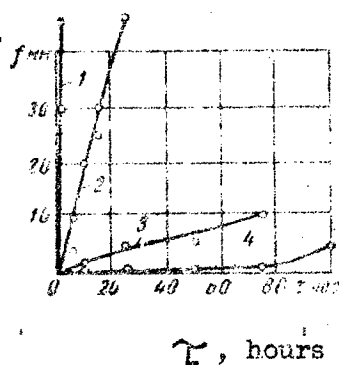


Figure 11. Creeping (by the bending method): 1 - solid solutions of nickel with niobium (10 % Nb) and tantalum (715 % Ta) and compounds, 2 -  $\text{Ni}_3\text{Ti}$ , 3 -  $\text{Ni}_3\text{Ta}$ , 4 -  $\text{Ni}_3\text{Nb}$  at  $1030^{\circ}$  and  $\sigma = 6 \text{ kg/mm}^2$ .

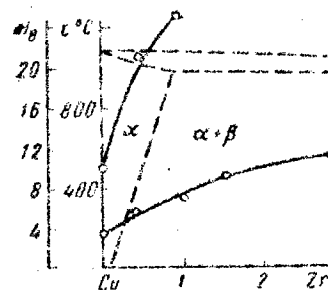


Figure 12. Diagram of composition versus heat resistance for alloys of the system Cu-Zr at the corresponding temperature of  $0.6 T_{\text{melt}}$ .

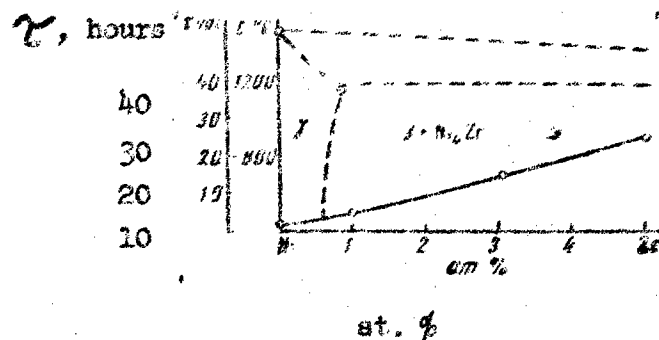


Figure 13. Diagram of composition versus heat resistance for alloys of the system Ni-Zr for 800° and  $\sigma = 4 \text{ kg/mm}^2$ ,  $\tau$  is the time to reach an indicator reading of 5 mm.

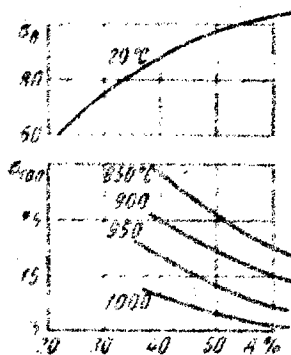


Figure 14. Limits of short-term ( $\sigma \text{ kg/mm}^2$ ) and long-term ( $\sigma_{100} \text{ kg/mm}^2$ ) resistance of TiC as a function of the percentage of bonding of the alloy Ni-Co-Cr.

(A %)